Astrophysical Polarimetric Signature Against TeV Fundamental Planck Scale

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Abstract

I present the analysis of data of astrophysical polarimetric observations that gives the signature of the fundamental extra dimension Planck scale magnitude essentially higher than $1TeV$. Magnetic conversion of photons into the fundamental particles (scalars, gravitons) is the probable mechanism that can produce noticeable amount of polarization of optical radiation of astrophysical objects, especially, of distant extragalactic sources. The results of magnetic conversion process of optical light of extragalactic sources are presented for a number of situations including: (a) intergalactic magnetic field, (b) galaxy cluster magnetic field, (c) magnetic conversion in the typical galaxy magnetic field, (d) magnetic conversion of CMB radiation.

1 Introduction

There is now a very popular idea of the existence of additional dimensions beyond the four ones that we explore in our every day life. A possibility that the Universe has additional compactified spatial dimensions has been long discussed (see the classical papers by Kaluza (1921) and Klein (1926)). This idea has been successfully developed by modern string theory (see the review by Green et al. (1987)). Recently this idea has been combined with Grand Unification Theory of Particle Physics.

The most outstanding problem in modern physics is to explain the extraordinary difference between the electroweak scale $M_{EW} = 10^3 GeV$ and the four-dimensional Planck scale $M_p = 10^{19}$ Gev. The various scenarios have been proposed. For example, the Standard Model (SM) of Particle Physics is localized on a three dimensional brane in a higher dimensional space with large compactified space-like extra dimensions. In a model suggested by Arkani-Hamed et al.(1998,1999), the matter is confined to a 3-brane while the gravity propagates in extra dimensions of a sub-millimeter size. These new dimensions should be sufficiently compact so as to escape trivial detection.

The main exciting consequence of these new theories is possibility that the Planck, string and Grand Unification scales can all be significantly lower than it was previously thought, perhaps as low as few TeV (see, far example, Antoniadis (1990), Lykken(1996), Shiu and Tye (1998), Antoniadis and Baches (1999), Kubyshkin (2001),etc). Also in theories with

standard model of gauge bosons propagating in TeV^{-1}-size extra dimensions, their Kaluza-Klein states can interact with the rest of SM particles confined to the 3-brane.

Many physicists try to look for possible signals for this interaction in the present high-energy collider data, and estimate sensitivity that can be reached by the next generation of collider experiments (see recent publications by Bordag et al. (2000), Lykken and Nandi (2000), Cheung and Landsberg (2001), McMullen and Nandi (2001) and Muck et al. (2001)).

"n" extra dimensions are compactified at the scale R^{-1}, where the size R is related to the four-dimensional Planck scale M_p via the relation:

$$M_p^2 = M_s^{n+2} R^n, \tag{1}$$

where the new scale M_s is the fundamental $(4+n)$- dimensional Planck scale which appears of the same order as the string scale.

More recent studies have shown that there could be possible scenarios of stringly nature where $1/R$ and M_s may be lowered independently of M_p by several of many orders of magnitude. In particular, the scenario is now very popular with radical possibility that M_s of order TeV. In such a way M_s represents the only fundamental scale in the Universe at which unification of all forces of nature occurs. Arkani-Hamed et al.(1998) have developed this scenario and made the conclusion that the compactification radius is related to the higher dimensional gravitational interactions lies in the sub-mm range, i.e. $1/R < 10^{-3} eV$. They hope that Cavendish-type experiments may potentially test the model by observing deviations from Newron's law at such small distances. Their model can be also tested by high-energy collider experiments.

One of the direct consequence of extra dimension universe is possible variation of the fine structure constant, especially, at high redshifts. Dirac (1938) was among the first to suggest that fundamental constants, such as the fine structure constant $\alpha = e^2/\hbar c$ could vary with time. The interest in varying constant theories has recently risen with the increased popularity of above mentioned models with extra dimensions (see, for instance, Damour and Dyson(1996), S. Caroll(1998), Varshalovich et al.(2000), Murphy et al.(2001a,b), Webb et al.(2001), Barrow et al.(2001)).

The various astrophysical effects can lead to constraints on the effective fundamental scale M_s (see the excellent last review by Kubyshkin (2001), Table 3 from this review and references therein).

The goal of this paper is to include in astrophysical effects that can give essential bounds on M_s the recent polarimetric observations of extragalactic objects with high redshifts (active galaxy nuclei (AGNs), quasars (QSOs), radiogalaxies, galaxy clusters, etc). The central idea is to investigate the new process that can produce a noticeable amount of polarized light into galaxy and galaxy cluster's magnetic field, and also into intergalactic magnetic field. I mean the process of the magnetic conversion of radiation into (pseudo) scalars and gravitons. This process has been considered as the real mechanism for production of polarized light in astrophysics by Raffelt and Stodolsky (1988), Harari and Sikivie (1992), Gnedin and Krasnikov (1992), Gnedin (1994). Raffelt and Stodolsky have considered this process and for gravitons. Let us mentioned that the process of magnetic conversion was specially explored due to searches for axions.

I shall show below that polarimetry of extragalactic objects gives more strong bounds on the fundamental scale M_s than this is to be expected from collider experiments and other

astrophysical effects (cooling of the Universe, SN1987 cooling and cosmic diffuse gamma radiation).

2   Magnetic Conversion of Photons into Fundamental Particles

Grand Unification theory (GUT) requires the existence of coupling between photons and fundamental particles. This coupling is determined by Lagrangian term (for scalars):

$$-\frac{1}{M_s}\phi F^{\mu\nu}F_{\mu\nu}, \tag{2}$$

where F is the tensor of electromagnetic field and ϕ is a scalar field.

The theory gives the following expression for probability of conversion of definitely polarized photons $W_{||}$ into scalar particles (Raffelt and Stodolsky (1988), Gnedin (1994)):

$$W_{||} = \frac{L_p^2}{L_B^2 + L_p^2} \sin^2\left(\frac{1}{2}\frac{BL_{coh}}{M_s}\sqrt{1 + L_B^2/L_p^2}\right), \tag{3}$$

where B is the magnetic field strength, L_{coh} is the coherence length of magnetic field, $L_B = 2\pi M_s/B$ and $L_p = 2\pi\omega/\omega_p^2$ are the oscillation lengths of magnetic conversion into vacuum magnetic field and into plasma, respectively. Only one polarization state for which the electric vector lies into the plane containing the magnetic field and line of sight directions is transformed. Here and below the symbol B means really the projection of the vector B on the this plane.

The Eq.(3) is valid only if the condition $L_B, L_p < 2\pi\omega/m_\phi$ takes place, where m_ϕ is the mass of a scalar. Therefore, our consideration is restricted only by low mass and massless scalars or gravitons.

For the case of vacuum, i.e. when $L_p \gg L_B$ Eq.(3) is very simplified and takes a form:

$$W_{||} = \sin^2\left(\frac{1}{2}\frac{BL_{coh}}{M_s}\right) \approx \frac{B^2L_{coh}^2}{4M_s^2} \tag{4}$$

if the condition takes $BL_{coh} \ll M_s$.

The degree of linear polarization p_l can be easily found by

$$P_l = \frac{I_\perp - I_{||}(1 - W_{||})}{I_\perp + I_{||}(1 - W_{||})} \approx W_{||}/2 \tag{5}$$

if one has deal with nonpolarized light, i.e. $I_{||} = I_\perp = I_0/2$ and $W_{||} \ll 1$.

Now the main problem consists in the estimation of the magnitudes of B and L_{coh} for real astrophysical conditions.

3 Magnetic Field Strength and the Coherent Length in the Universe

Magnetic field play an important role in practically all astrophysical phenomena. There are some of the reviews and papers concerning to the origin and possible effects of magnetic fields in the Universe and also to the current status of the art of observations of cosmic magnetic fields (see, for example, Kronberg(1994) Grasso and Rubinstein(2001), Carilli and Taylor (2001), Dolgov (2001), Gnedin et al.(2000), Furlanetto and Loeb (2001)).

Let us start with situation of magnetic fields in galaxies. The interstellar magnetic field in the Milky Way has been determined by several methods which gave valuable information about the amplitude and spatial structure of the field. The average field strength is $3 - 4 microG$. Such a strength corresponds to an approximate energy equipartition between the magnetic field, the cosmic rays confined in the Galaxy, and the small-scale turbulent motion.

Observations on a large number of Abel clusters, some of which have a measured X-ray emission, have given valuable information on fields in cluster of galaxies (Kim et al.1991). Magnetic field strength in the inter cluster medium (ICM) can be quite well estimate by the phenomenological relation (Grasso and Rubinstein 2001):

$$B_{ICM} \approx 2\mu G \left(\frac{L_{coh}}{10 kpc} \right)^{-1/2} h_{50}^{-1}. \tag{6}$$

Typical values of L_{coh} are 10-100 kpc which correspond to field magnitudes of $10 - 1\mu G$. For example, the case of the Coma Cluster a core magnetic field strength reaches $B \approx 8.3 h_{100}^{1/2} \mu G$ at scales of about 1 kpc. An exciting example of clusters with a strong magnetic field is the Hydra A cluster for which the Rotation Measure (RM) implies a 6 microGauss field over 100 kpc superimposed with a tangled field of strength 30 microGauss (Taylor and Perley,1993). The high-resolution images of radio sources embedded in galaxy clusters show evidence of strong magnetic fields in the cluster regions, and also in the regions of cool fronts and cool fluxes (Carilli and Taylor, 2001). The typical central field strength is approximately 10 -30 microGauss with the peak values as large as 70 micro Gauss.

Furlanetto and Loeb (2001) gave an estimation of the magnetic field strength in the diffuse intergalactic medium (IGM) assuming flux conservation for out flows from QSOs that inevitably pollute IGM. They obtained $B_{IGM} \sim 10^{-9}G$ with the coherence length 1 Mpc. The observational constraints on an IGM field imply more soft bounds, requiring only that $B_{IGM} < 106-8(L_{coh}/Mpc)^{-1/2}G$ with use of the currently popular ΛCDM model.

The last exciting result has been recently obtained by Hutsemekers and Lamy (2000), who discovered the existence of coherent orientations of QSO polarization vectors on cosmological scales. Considering a sample of 170 optically polarized QSOs with accurate polarization measurements they found that QSO polarization vectors are not randomly oriented on the sky as naturally expected. They claim that these observations give an evidence for the presence of correlations, probably, IGM magnetic field on spatial scales $L_{coh} \sim 10^3 h^{-1}$ Mpc at redshifts $z \approx 1 - 2$.

Now let us start with estimation of the fundamental extra dimension Planck scale M_s with use of recent polarimetric data of observations of QSOs and AGNs in optical range.

4. Estimation of Fundamental Extra Dimension Planck Scale from Optical Polarimetric Data.

3.1 Magnetic Photon Conversion in the IGM

We shall make our estimations using approximation by Furlanetto and Loeb (2001) accepting the dependence of IGM magnetic field strength on coherence length in a form

$$B \equiv B_{ICM} = 10^{-9} \left(L_{coh}/1Mpc \right)^{-1/2} G. \tag{7}$$

The IGM electron density is

$$n_e = \Omega_b h^2 \times 10^{-5}(1+z)^3 cm^{-3} \approx 2 \times 10^{-7}(1+z)^3 cm^{-3}. \tag{8}$$

The the oscillations lengths are:

$$L_p = \frac{2\pi\omega(1+z)}{\omega_p^2} \approx 2 \times 10^{29} \left(\frac{\omega}{3eV} \right) \frac{1}{(1+z)^2} eV^{-1},$$

$$L_B = \frac{2\pi M_s}{B} = 10^{23} \left(\frac{10^{-9}G}{B} \right) \left(\frac{M_s}{1TeV} \right) eV^{-1}, \tag{9}$$

where ω_p is the plasma frequency.

The commonly accepted system units $\hbar = c = 1$ is here used. Eq.(9) means that $L_B < L_p$ if $M_s < 10^5$ TeV. We consider the case of high redshift objects with $z \leq 2$. For the extragalactic objects with $z \leq 1$ the condition $M_s \leq 10^6$ TeV requires that $L_B \leq L_p$.

Now let calculate the value of extra dimension Planck scale directly from Eq.(3). The polarization level at 0.01 is quite well consistent to observable data (see review Koratkar and Blaes (1999) and references therein and Hutsemekers and Lamy (2000)). The coherence length $L_{coh} \sim 1Mpc$ appears to be larger that the oscillations lengthes L_p and L_B but $L_p < L_B$. Then

$$P_l \approx 0.01 \approx \frac{L_p^2}{L_B^2} \sin^2 \left(\frac{1}{2} \frac{BL_{coh}}{M_s} \sqrt{1 + L_B^2/L_p^2} \right). \tag{10}$$

From ratio $L_p^2/L_B^2 \approx 10^{-2}$ it follows:

$$M_s \approx 10^6 TeV \left(\frac{B}{10^{-9}G} \right) \left(\frac{\omega}{3eV} \right) \tag{11}$$

for $z \approx 2$.

Let us put a question what IGM magnetic field strength corresponds to $M_s \approx 1TeV$. One needs to require two conditions: $L_B \gg L_{coh} \gg L_p$ and $L_{coh}/L_B \sim 0.1$. The last condition is required that polarization P_l exists at the observable level of 1 percent.. One can get from these conditions the relation $2\pi M_s/B > 10Mpc$ and $B < 410^{-18}G$. This IGM magnetic field seems to be very small and inconsistent with recent observable polarimetric data obtained by Hutsemekers and Lamy (2000).

3.2 Magnetic Photon Conversion in Fields of Galaxy Clusters

Let us estimate the magnetic photon conversion rate in cluster magnetic fields using the data from most recent review by Carilli and Taylor (2001) (see Table 1 from this review). The typical magnetic field strength in the cluster is to be $B \approx 10\mu G$ and the coherence length (cell) size is 10 kpc. The most commonly accepted value of the central density of a cluster is $n_0 \approx 10^{-3} - 10^2 cm^{-3}$. For this situation the parameters of magnetic conversion process are:

$$L_B \approx 10^{20} \left(\frac{M_s}{10 TeV} \right) \left(\frac{10\mu G}{B} \right) eV^{-1},$$

$$L_p \approx 6 \times 10^{23} \left(\frac{\omega}{3eV} \right) \left(\frac{10^{-2} cm^{-3}}{n_0} \right) eV^{-1}. \tag{12}$$

Because of $L_B \ll L_p \ll L_{coh}$ the strong oscillations in magnetic conversion process take place and one can expect the polarization degree for embedded or background optical source at the high level $p_l \sim 100\%$, that contradicts really to observable data.

For $n_0 \approx 10^{-3} cm^{-3}$ and the observable polarization level $\approx 1\%$ one can estimate the value of the effective Planck scale as $M_s \approx 10^7 TeV$.

3.3 Magnetic Photon Conversion in Galaxies

The basic parameters of magnetic conversion into typical galaxy are:

$$L_B \approx 3 \times 10^{19} \left(\frac{M_s}{1 TeV} \right) \left(\frac{3 \times 10^{-6} G}{B} \right) eV^{-1},$$

$$L_p \approx 2 \times 10^{21} \left(\frac{\omega}{3eV} \right) \left(\frac{1 cm^{-3}}{n_e} \right) eV^{-1}. \tag{13}$$

Here $n_e \approx 1 cm^{-3}$ is the average electron density in a typical galaxy. $M_s \sim 1 TeV$ is excluded because this case gives such high polarization value $\approx 100\%$, more higher compare to observed interstellar polarization that has a level at some percents.

If one wants to estimate the contribution of magnetic conversion process, this process needs to provide the level of polarization at least not higher than the interstellar polarization.

For the case of strong coupling photons to scalars when $L_p, L_B < L_{coh}$, the condition $L_p < L_B$ is required for obtaining the polarization comparable to interstellar one from the nearest stars located at the distance $L \approx 100pc$, and then $M_s \approx 10^3 TeV$.

The case of weak coupling is accomplished if only $L_p > L_B > L_{coh}$. In this case magnetic conversion polarization is determined by Eq.(4) with replace of L_{coh} on L. If, for example, $n_e \approx 10^{-4}$ (low density regions of a galaxy), the Eq.(4) provides by comparison with the interstellar polarization $M_s \geq 3 * 10^6 TeV$.

It is interesting to notice that there are polarimetric observations that show the violation of interstellar polarization wavelength curve for a number of stars from the famous Serkowskii law, the observable polarization being increased in near UV range (this fact is in favor of magnetic conversion mechanism). Of course, there exists another explanation of this discrepancy that looks not so exotic (see Martin et al.1999).

4 Magnetic Photon Conversion as a Cause of Dependence of Fraction Polarized QSOs on Redshift

Impey et al.(1991), Wills et al.(1992) and Carilli et al.(2000) have shown that a fraction of extragalactic sources (AGNs, QSOs, superluminous IR galaxies) with noticeable optical polarization magnitude is really decreasing with increase of redshift magnitude. There are probably two ways for explanation of this phenomenon: this is an intrinsic cause due , for example, to Faraday depolarization in accreting disks around supermassive black holes (see Gnedin and Silant'ev (1997, 2001)) and the external cause due to depolarization in extended environment and IGM.

We are here considering the second possibility suggesting that depolarization is produced by birefrigent effect of magnetic photon conversion into low mass scalars or gravitons (see Raffelt and Stodolsky (1988), Gnedin and Krasnikov (1992)), the rotating angle being not dependent on wavelength.

In the case of strong coupling when $L_B \ll L_p \ll L_{coh}$ the optical radiation of distant extragalactic sources should be completely depolarized, but it is not this case. In the case of weak coupling when the rotation angle is determined by the following expression (Raffelt and Stodolsky (1988)):

$$\Theta = \frac{1}{8} \frac{B^2 L_{coh}^2}{M_s^2} \approx 1,\tag{14}$$

there is noncomplete depolarization that corresponds better to observable data.

Then we obtain the following estimation of the fundamental extra dimension Planck scale:

$$M_s \geq 3 \times 10^6 TeV \left(\frac{B}{10^{-9}G}\right) \left(\frac{L_{coh}}{1Mpc}\right).\tag{15}$$

Of course the Eq.(15) does not exclude the case $M_s \approx 1TeV$ if the magnetic field of IGM takes magnitude $10^{-15}G$ for $z \approx 1 - 2$, but this fact seems quite unreal.

5 Magnetic Photon Conversion Process and CMB

The question is arising how the magnetic conversion of photons to fundamental particles affects on the CMB, in particular, producing its polarization. We are going to discuss this problem in detail in the separate paper. Here we would like only roughly to estimate the effect. For the CMB the parameters of magnetic conversion are:

$$L_B \approx 10^{23} \left(\frac{M_s}{1TeV}\right) \left(\frac{10^{-9}G}{B}\right) eV^{-1},$$

$$L_p \approx 10^{26}(1 + z)^{-2}eV^{-1}.\tag{16}$$

and $L_{coh} > L_p > L_B$ that means that strong coupling is acting in this case. The degree of polarization of CMB would be high at the level close to 100%. But more weak magnetic fields requires more high magnitude of the fundamental Planck scale. It means that the

Table 1: Effect of Magnetic Conversion on Polarimetric Data

Object of Polarimetric Observations in the optical range	Magnetic field B	Coherence length L_{coh}	Planck scale M_s
Intergalactic Medium	$B \leq 10^{-9}$G	$L_{coh} \sim 1$Mpc	$M_s \geq 10^6$TeV
Galaxy Clusters	$B \sim 10^{-5}$G	$L_{coh} \sim 10$kpc	$M_s \geq 10^7$TeV
Typical Galaxy	$B \sim 3 \times 10^{-6}$G	$L_{coh} \sim 100$pc	$M_s \geq 10^3$TeV
Fraction of Polarized QSOs and AGNs	$B \leq 10^{-9}$G	L_{coh} 1Mpc	$M_s \leq 10^7$TeV
Cosmic Microwave Background	$B \leq 10^{-9}$G	L_{coh} $1Mpc$	$M_s \leq 10^3$

validity of Eq.(16) requires the strong bounds on IGM magnetic field and the fundamental Planck scale, namely,

$$\left(\frac{10^{-9}G}{B}\right)\left(\frac{M_s}{1TeV}\right) \leq 10^3(1+z)^{-2}. \tag{17}$$

This result provides that if $M_s \geq 1TeV$ one can expect the strong polarization of CMB at angular scales $< 1arcmin$.

6 Conclusions

Though our results does not completely exclude the fundamental Planck scale magnitude $M_s \sim 1TeV$, the available polarimetric data, especially, for extragalactic sources makes the effective Planck scale magnitude $M_s \gg 1TeV$ more probable.

Our results can be presented by the following Table 1.

At last, let us remind that we considered only the process of photon magnetic conversion into low mass and massless scalars and gravitons. The case of massive scalars and gravitons requires special consideration.

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